RISØ

Risø-R-567

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Edited by B. Micheelsen and F. List

Risø National Laboratory, DK-4000 Roskilde, Denmark
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DEPARTMENT OF ENERGY TECHNOLOGY
ANNUAL PROGRESS REPORT
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Abstract. The general development of the Department of Energy Technology at Risø during 1988 is presented, and the activities within the major subject fields are described in some detail. Lists of staff and publications are included. Partial Contents

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CONTENTS

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1. DEVELOPMENT DURING 1988

1.1. The Department of Energy Technology

As a consequence of earlier organizational changes at Risø the environmental modelling group was transferred from The Department of Energy Technology to the Department of Systems Analysis in the beginning of the year. The Department of Energy Technology has now research and development work in the following organizational units:

- the reactor physics group
- the section of combustion research
- the reservoir group
- the Danish Reactor no. 1

During the year the reactor physicist began - in collaboration with other Risø staff and staff from The Technical University of Copenhagen - to collect data and knowledge on nuclear reactors with the purpose of establishing and maintaining a general knowledge of reactor types in the vicinity of Denmark. This knowledge is being collected in reports for each reactor type in Sweden, The Federal Republic of Germany, and the German Democratic Republic. Some of the data for the reactors and the development of their safety features have been difficult to get access to.

The 10-MW Danish research reactor no. 3 was changed from 93% enriched fuel to 20% enriched, and the reactor physicist has supported this in a major calculation effort.

In the combustion research and development the year began with a heavy experimental effort on the 2-MW circulating fluid bed (CFB), where coal and straw mixtures were used as fuel. This work was succeded by work on a 20-MW CFB in collaboration with Aalborg Boilers A/S and the Danish utility Midtkraft. The combustion research section has completed a 2-MW pulverized tunnel furnace with the purpose of making detailed measurements by laser diognostic and laboratory testing of three dimensional particle/gas models. Furthermore, studies of gasification of biomass and coal were initiated during the year.

The reservoir group has worked on basin modelling studies for the Central Trough in the North Sea. This was done in a collaboration effort with the Danish Geological Survey and Dansk Olie- og Naturgasproduktion A/S. The study used a three-dimensional computer model by Arif M. Yükler, who worked as a consultant. During the year this working group was cast into a commercial working unit, called Danish Modelling Group, the purpose of which is to develop basin models, undertake basin modelling studies, and sell these two products.

1.2. The Reactor Physics Group

The main activities in the Reactor Physics Group have been:

- implementation of a 2-group nodal expansion method for the flux solution in the BWR core simulator code COSIMA

- introduction of "control rod history" in COSIMA

- changes in the LEWARD cross section generating programme related to the above mentioned changes in COSIMA

- gamma radiation estimations for the TOKAMAK fusion reactor, NET

- supporting calculations for other departments, mostly in connection with DR3 utilization

- calculation for the conversion of the DR3 to 20% enriched uranium

- implementation and modification of codes for calculation of aerosol behaviour, and the utilization of these, mostly within the Nordic AKTI research programme.

The BWR core simulator programme NOTAM has been modified in several ways. The former method of flux solution was based on a "1 1/2" group method, relying on some empirical constants. Some years ago a study for the Ph.D. degree produced an efficient 2-group method, based on nodal expansion of the flux. This method has been introduced in NOTAM and the new programme named COSIMA.

A number of other improvements were made as well, the most prominent being a newly developed capability to take into account the history of control rod movements, a deficiency in NOTAM, which was recognized as very serious. In section 2 the details about this important development are given. The changes in COSIMA necessitated corresponding modifications in the LEWARD programme, which supplies the cross section tables for COSIMA. The accounting of control rod history requires a much bigger volume of cross sections than before, which again necessitated the programming of restart/dump facilities into LEWARD.

The work on the development of a method for calculation of gamma radiation levels close to a TOKAMAK fusion reactor has been finished with a calculation on the newest geometrical proposal.

A large number of calculations with different reactor physics codes have been performed as support for:

- DR3 fuel management (a programme package has been delivered to the DR3 staff, which is now able to do most routine calculations themselves).

- conversion of DR3 from 93% to 20% enriched uranium

- silicium irradiation in DR3 for semi-conductor production (the design of a new horizontal irradiation facility has required a large calculational effort)

- fission gas release examinations of highly irradiated specimens of power reactor fuels.

1.3. Section of Combustion Research

During 1988 a strategy plan for combustion research and development at Risø was finished. The main content of the plan is that the fundamental combustion research must be strengthened both in quantity and quality. At the same time the development work for utilities and industry shall be expanded.

Coal and biomass combustion, and implemention of measurement techniques for combustion and environmental problems, have formed the major part of the work during the year.

The 2-MW circulating fluid bed which was rebuilt in 1987 to include facilities for straw handling was in the beginning of 1988 used for combustion experiments with a mixture of coal and straw. These experiments were carried out in a close cooperation with Aalborg Boilers A/S. The straw was cut and blown into the reactor by means of a pneumatic transport line. During the first 6 months 1500 hours of operation have been obtained. The results have been used by Aalborg Boilers to design a 20-MW circulating fluid bed demonstration plant to be located in Aarhus at the utility company Midtkraft. This plant is due to be built in 1989 in a cooperation between Aalborg Boilers, Midtkraft and Risø. Risø will be responsible for the instrumentation, the measuring system, and the analysis of the measurements.

A major step was reached in the last part of 1988 as a 2-MW pulverized tunnel furnace was taken into operation. This facility will be used both for laser diagnostic experiments (velocity, particle size/-concentration, and gas composition) and as a tool for laboratory testing of 3-dimensional particle/gas models. The furnace will also be used as a "source term" for development of $deNO_x/SO_x$ equipment in our cooperation with Vølund A/S.

To make measurements by Laser Doppler Anemometer (LDA) possible in practice a specially designed traversing system has been constructed and built. To select the optimum method for particle sizing in the furnace a theoretical study of light scattering has been performed. The result has been that forward scatter detection must be used to make size measurements on irregular particles possible. In cooperation with Harwell Laboratory in England a particle sizing instrument has been constructed, and the first measurements are expected to take place April 1989.

As a part of the fundamental combustion research a laminar entrained flow reactor was built, and the first experiments have been performed. The design of the system was modified during the year as a consequence of measurements performed with the Laser Doppler Anemometer, which proved that the first design did not have laminar flow because of the turbulence created at the inlet of the reactor.

A cooperation project between Aalborg Boilers A/S, dk-TEKNIK and Risø concerning gasification of straw in a fluid bed system has been started. The preliminary finding indicates that a fluid bed solution might be an attractive one.

The cooperation project, between The Laboratory for Heating and Air Conditioning at the Technical University of Denmark and Risø, on the development of a 3-dimensional turbulent gas/particle flow model is being continued. The model has now reached a stage where comparison with the experimental results from the 2-MW tunnel furnace is feasible.

A combined experimental and theoretical study of the interphase friction in two-phase stratified flow has been carried out as a joint project between Risø, LICconsult and the Technical University of Denmark. The measurements have been performed with air/water mixtures at horizontal or near horizontal flow. The equivalent interfacial roughness has been calculated.

1 . The Reservoir Group

The work has been concentrated on two subjects of interest for hydrocarbon exploration and recovery, i.e. basin modelling and reservoir technology.

Basin modelling is directed towards a computer simulation of the history of sedimentary basins, based on basin analysis, including a description of the amount of organic matter, its conversion to hydrocarbons, the migration of the oil and gas and their accumulation in the reservoir rocks.

A Danish basin modelling group, including the Geological Survey of Denmark, Risø National Laboratory, the Technical University of Denmark, Dansk Olie- og Naturgasproduktion A/S and the universities of Copenhagen and Aarhus have performed studies for basins in the Danish area. This work was done in collaboration with the consultants Gordon S. Speers and Arif M. Yükler utilizing the basin simulators developed by Yükler. This work was supplemented by a research project concerning the further development of basin simulators, financed by the Danish Energy Research Programme.

In order to utilize the experience gained through this work and in order to promote the further development of basin modelling the Geological Survey, Risø National Laboratory and Dansk Olie- og Naturgasproduktion A/S have formed the Danish Modelling Group for the international marketing of basin studies as well as software for this purpose in collaboration with Arif M. Yükler.

The development work on the reservoir simulator, COSI, has been continued with special emphasis on the simulation for fractured reservoirs. Special features for the description of the coupling between the fracture system and the rock matrix have been developed, which will be the subject of a paper at the SPE-Conference in Houston in February 1989. At the same time Risø participates with solutions for a number of bench mark problems concerning fractured reservoirs.

Further experiments with sand packs have been performed at the Technical University of Denmark to model the displacement processes in fractured reservoirs. These experiments as well as experiments reported in literature have been simulated with good results. Displacement experiments with carbonate plugs with artificially induced fractures are now under way at the Geological Survey. A computer assisted method for the determination of relative permeabilities is now so far advanced that the installation of the necessary hardware and software at the Geological Survey is now under way.

For some reservoir studies, especially for the study of improved oil recovery schemes, a compositional treatment of the reservoir fluids is needed. A compositional simulation, as may be performed with the above mentioned COSI, is however very costly in computer time, if a large number of components is used. A project aimed at the determination of the minimum of components needed for the specific resevoir problem studied has been started in 1988.

1.5. Danish Reactor DR 1

The reactor has been used for educational purposes only. A number of students from technical universities in Denmark and Sweden have carried out experiments at the reactor over periods of 1-3 weeks, and 53 high school classes have carried out one-day experiments. The total number of students has been more than 900.

2. ACTIVITIES OF THE DEPARTMENT

2.1. New Features in the COSIMA Boiling Water Reactor Core Simulator

Comparison of calculations with our BWR programme complex LEWARD/NOTAM and measurements performed at the Quad Cities reactor showed a satisfactory agreement at low burn-up, but increasing discrepancies at higher burn-up.

Quite a number of non-satisfactory solutions to the physical problems could be pointed at in NOTAM, and it was decided to try to improve at least some of them.

In this brief section, three of the major changes performed will be touched upon.

2.1.1. Exchange of the TRILUX nodal flux solution method in "1 1/2" group with a true 2-group method known as the NEM, Nodal Expansion Method

The "1 1/2" groups refer to a treatment where thermal leakage is ignored, an assumption which is not at all bad for LWR, although some doubts may exist as to the validity at high steam bubble contents.

With the NEM 2-group method that problem is in any case eliminated. The NEM method was developed in the course of a Ph.D. study some years ago and its merits were compared to other methods (CHRISTENSEN, 1985).

2.1.2. Introduction of "Control Rod History"

In COSIMA, the neutron cross sections at each point of the reactor are obtained by interpolation in large tables (supplied as data from the LEWARD programme). The cross sections are dependent on a number of parameters:

1. The fuel type (characterized by e.g. enrichment, Gd-poison)
2. The burn-up
3. The life-time averaged void content
4. The actual void content
5. Control rod position (in or out)

As to the last parameter, the cross sections would refer either to a situation where the control rod was in and had been so from the start and up to the present time, or to a situation where the rod was out, and had been out the whole time. Obviously, this picture may often be wrong, and the following procedure was adapted to improve on the matter: Instead of two sets of cross sections, where either the control rod is in the whole time or out the whole time, many sets are now generated:

- A set where the burn-up history is entirely: control rod out.

- A set where the rod is inserted during the first burn-up step and withdrawn for the rest of the time.

- A set where the rod is inserted during the two first burn-up steps and withdrawn for the rest.

- And so on.

The result is a lot more data. If we have N burn-up stages, the new method will require (N+1)/2 as many data as before. N is often about 20-30.

Especially in the case of fuel assemblies holding Gd-poisoned pins, the efffect of control rod history is quite spectacular.

In Fig. 1. an example of the k_{inf} for an assembly with 3 Gd-pins (in a 49 pin assembly) is shown. It is seen that at least while the Gd is still present (up to 6-8000 MWd/tU) there is a real significant difference between the k_{inf}-values obtained in the "old" manner and now.

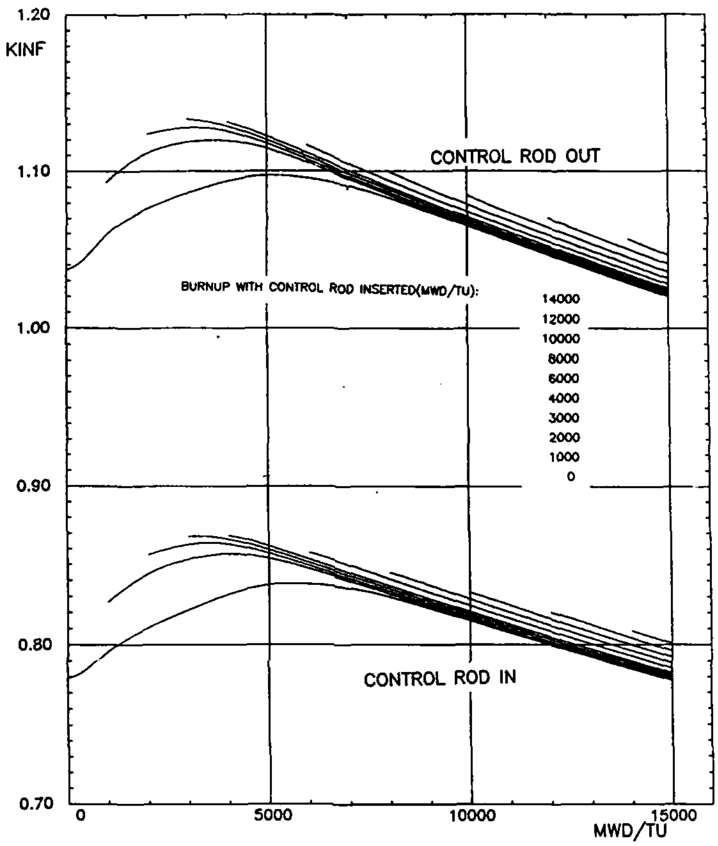


Fig. 1. K_{inf} as function of burn-up with and without control. Parameter is the burn-up, which has taken place with the control rod in.

2.1.3. Introduction of "instrument factors"

In a BWR the power distribution is continuously monitored by a number of TIP's (Traversing In-core Probes), which are either fission chambers or gamma-sensitive detectors. The TIP's are moving vertically in the narrow corner slits between 4 adjacent assemblies. To compare calculations with TIP-measurements it was up to now customary to take a simple average of the powers in the 4 relevant assemblies.

There were good reasons to suspect the validity of such averages being strictly proportional to the power of the 4 assemblies, and thus, with the other changes, the reaction rates in the TIP-positions were calculated as well for a fission chamber as for a gamma-sensitive ionization chamber and for a device simply measuring the temperature of an insulated metal block, which is heated by the gamma radiation.

These "instrument factors" are treated in COSIMA in the same way as the cross sections, i.e. interpolated in all the relevant parameters.

Fig. 2. shows the significance of calculating instrument factors, as well for their dependence on burn-up, as for their dependence on control rod position.

C.F. Højerup

REFERENCE

CHRISTENSEN, B. (1985). Three-dimensional Static and Dynamic Reactor Calculations by the Nodal Expansion Method. Risø National Laboratory. Risø-R-496.

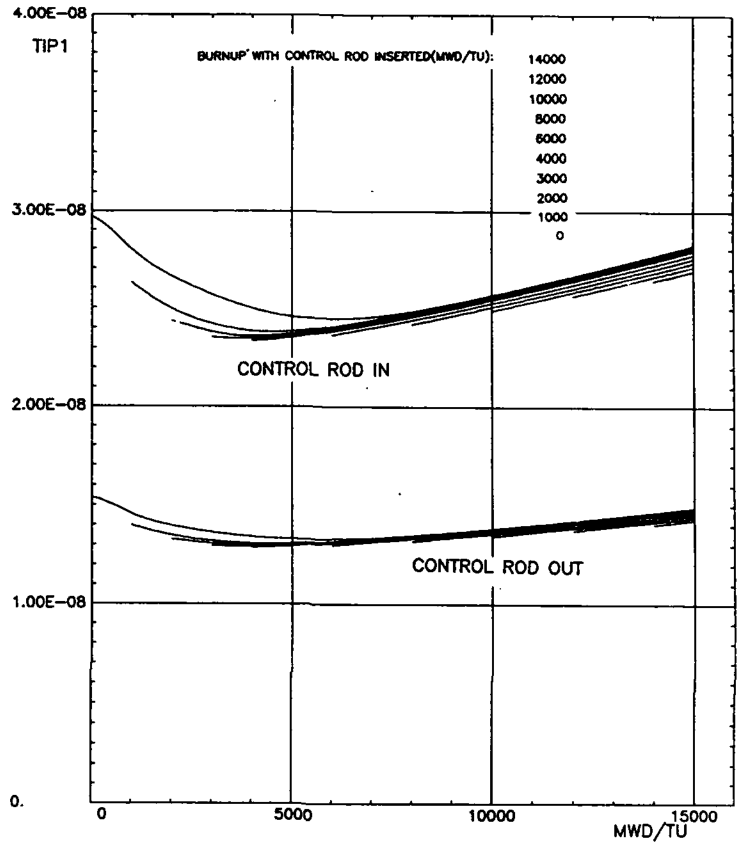


Fig. 2. Instrument factor for fission chamber (number of fissions per U-235 atom). Parameter is the burn-up which has taken place with the control rod in.

2.2. Flux Calculations in a New Horizontal Irradiation Facility in DR3

The irradiation facilities in the DR3 reactor for semi-conductor production by neutron transmutation doping of silicon is going to be increased and improved. The demand from the customers of an increasing uniformity and quality of the doping has necessitated a new horizontal facility if Risø wants to stay on the market for silicon doping.

Until now, the irradiation has only taken place in the vertical test tubes in the reactor with the drawback of the axial flux shape decreasing the homogeneity of the doping. By moving the silicon crystal very slowly through a horizontal test tube in the reactor, while the crystal itself rotates, a very homogeneous irradiation can be obtained.

The movement and irradiation time for each crystal is going to be controlled by an online PC on the basis of four flux measurements at fixed positions along the tube. This control system has been designed from several flux calculations with the simulator DR3/SIM (NONBØL, 1988) and the diffusion code DR3/DIFF2D.

The procedure for calculating the thermal flux is the following:

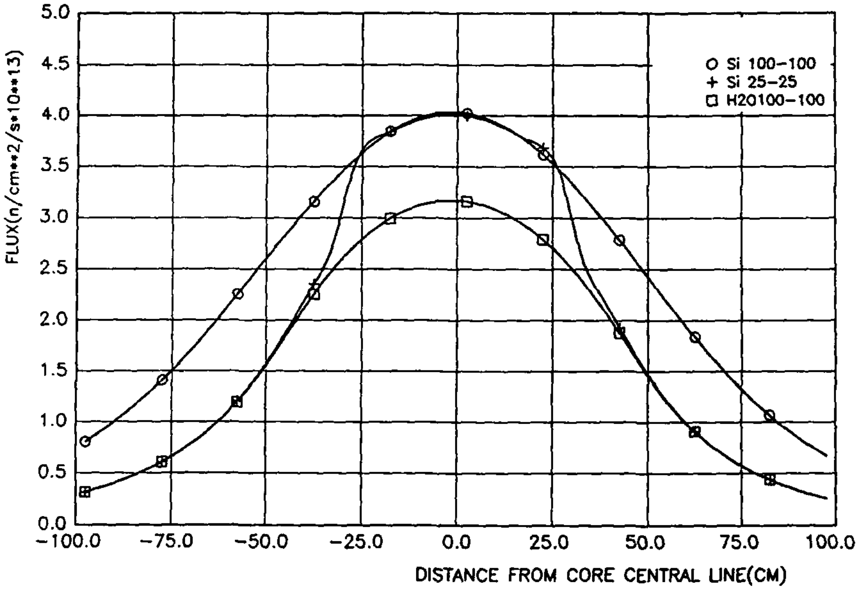
- Firstly a reference calculation is made with the three-dimensional code DR3/SIM, where the test tube is filled with light water.

- Secondly the two-dimensional code DR3/DIFF2D with cylindrical geometry is adjusted to the solution obtained with DR3/SIM.

- Finally the adjusted version of DR3/DIFF2D is used for the detailed flux analysis, where the test tube is filled with different materials.

The length of the test tube is 200 cm and it is filled with light water. Each silicon crystal has a diameter of 12.7cm and a length of 50cm. During the travel the crystal displaces the light water in the tube.

Fig. 3 shows some results from the flux calculation. The curve marked with squares is the case where the test tube is filled with light water and no silicon crystal. The curve marked with circles is the case where the test tube is filled with a silicon crystal of infinite length (200 cm). These two curves provide the boundaries for the flux during the travel of a silicon crystal with a final length. Thus the curve marked with crosses shows the flux in the case where a silicon crystal with a length of 50 cm is placed in the centre of the test tube.



<u>Fig. 3.</u> Thermal neutron flux in the new horizontal irradiation facility in DR 3.

The determination of the appropriate velocity of the crystal for a given dose is a compromise between the capacity of the facility and uniformity of the doping. E.g. the shortest irradiation time and the most inhomogeneous doping is obtained with the crystal placed in the centre of the tube without moving it. The longest irradiation time and the most homogeneous doping is obtained with constant velocity through the whole test tube. Fig. 4 shows the dose distribution in a 50 cm long silicon crystal at three different travelling times. It is clear how the case with longest travelling time gives the most homogeneous doping.

E. Nonbøl

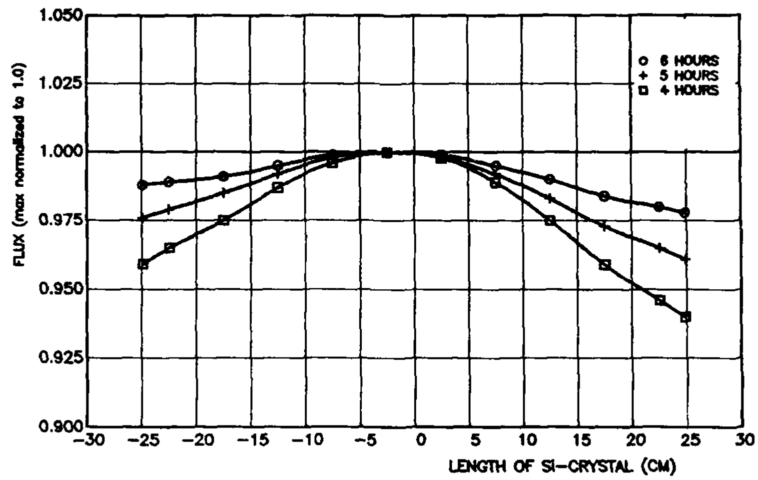


Fig. 4. Dose distribution in a silicon crystal irradiated with three different travelling times.

REFERENCE

NONBØL, E. (1988). A Three-Dimensional Simulator of a Heavy Water Research Reactor. Risø-I-376. 10p. (Also appearing in: Proceedings of the 1988 International Reactor Physics Conference. Jackson Hole, Wyoming, USA, September 18-22, 1988).

2.3. Implementation and Modification of Aerosol Codes

The aerosol transport codes TRAP-MELT3 and NAUA-5 have been modified and implemented in connection with the Nordic AKTI research programme.

TRAP-MELT3 and NAUA-5 are mechanistic aerosol transport codes. TRAP-MELT3 considers the primary system and NAUA-5 considers the containment.

It became necessary to modify TRAP-MELT3 at a number of points. The most important are:

- the method of solution of the thermal-hydraulic equations is now more efficient.

- the thermal-hydraulic calculations are now performed faster.

- the treatment of saturated vapours and of their condensation onto existing particles has been improved.

The flow chart of NAUA-5 has been modified in order to make the code more suitable for calculation of transients. The results of calculations of long term behaviour are not significantly affected by this.

P.B. Fynbo

2.4. The Temperature Calibration Laboratory

The Temperature Calibration Laboratory was accredited in 1978 by the Danish National Testing Board to carry out certified calibrations of temperature sensors in the -150°C to 1100°C range according to the International Practical Temperature Scale IPTS-68. In 1986 the accreditation was extended to cover the calibration of electrical resistances in the range 0-1100 Ohm and d.c. voltages in the range 0 - 1.1 V. The standard thermometers, the standard resistors, and the voltage standard cells in the Laboratory are traceable to the National Physical Laboratory, England.

The number of calibrations for external customers has increased steadily during the years. In 1988 the Laboratory has performed

222 jobs for external customers and 4 for other Risø departments. In all 1024 thermometers ranging from liquid-in-glass models to advanced digital types and 9 thermostats have been calibrated during the year. The calibrations have been made in the temperature range from -150°C to 1100°C which covers the whole range accredited.

A series of temperature measurements has been performed for external customers on site.

At a storage facility for natural gas the temperature transients at some critical points have been measured during blow down of the high pressure system.

A series of temperature measurements have been made in a waste incineration plant.

F. Andersen/N.E. Kaiser

2.5. Fundamental Combustion Research

A laminar entrained flow reactor has been built. The aim is to measure particle size and velocity, and eventually the temperature of coal char particles under controlled conditions. The measured parameters will be used to determine overall particle burning rates. To determine the fundamental parameters describing a particle burning rate, it is necessary to know the temperature history of the particle precisely, either experimentally or with a suitable predictive model, so that reaction rate constants may be extracted from the reactor data.

During building and testing of the flow reactor, the Laser Doppler Anemometer proved to be very useful. It showed that the first version of the laminar flow reactor did not have laminar flow at the entrance and so the reactor was modified.

The combustion process of the particle has been modelled in order to obtain a better understanding of the experimental results. The modelling system includes a finite-difference code predicting the gas phase flow and temperature fields in the reactor and a model that accounts for the particle heating rates and residence time as well as the combustion processes.

Risø National Laboratory, the Technical University of Denmark, and the utilities initiated just before the end of the year a new project concerning pyrolysis and ignition of coal particles.

L. Holst Sørensen

2.6. 2-MW Circulating Fluid Bed Test Facility

A 2-MW Circulating Fluid Bed test facility was built at Risø during 1987 as part of a cooperation between Risø National Laboratory and the Danish boiler manufacturer Aalborg Boilers A/S. The facility was built as a boiler producing 2.2 t/h of superheated steam at 10 bar, 400° C, and the fuel consisted of coal, straw, or mixtures of these.

A research programme made for the utility company Midtkraft I/S was terminated in June 1988. The aim of the programme was to show how the facility operates in different load situations. One of the main advantages of a plant like this is the ability to control the combustion rate and temperature giving a great fuel flexibility. Emissions of nitrogen oxides (NO_x) can be kept at a minimum at temperatures about 850° C and Sulphur dioxides (SO_2) can be reduced by adding limestone to the coal. In this programme different types of Danish limestone have been tested for their desulphurization capabilities.

The straw was cut up and blown into the reactor by means of a pneumatic transport line. Feeding straw pneumatically has caused some difficulties, mainly because of the relatively high water content in the straw used. These transport difficulties caused some delays in the test programme.

During the first 6 months the facility has been operating for approximately 1500 hours. The results have been used by Aalborg Boilers to design a larger 20-MW circulating fluid bed demonstration plant at Midtkraft in Århus. This plant is due to be built in 1989 in a cooperation between Aalborg Boilers, Midtkraft and Risø, in which Risø will be responsible for the instrumentation, the measuring system and the analysis of the measurements.

Lars Christiansen

2.7. Experimental Investigation of Pulverized Coal Burners

In the process of construction of pulverized coal burners with a small emission of NO_x it is important to have a better knowledge of the processes in the near burner field. In this project an experimental investigation of the flow field and the combustion characteristics in the near burner field will be done.

The experimental facility was built during 1988. The facility includes a coal mill (Fig. 5), a tunnel furnace with a maximum rated power of 2 MW (Fig. 6), and a flue gas cleaning system. It will be possible to conduct investigations of local conditions in the furnace and to test flue gas cleaning processes.

The furnace is at present equipped with a 0.7-MW swirling type burner. As shown in Fig. 6 the furnace is built of 11 calorimetric sections. It is possible to insert refractory lined rings inside the sections, and all sections have measuring ports to make local measurements possible in the whole furnace.

The coal handling system consists of a coal mill and coal feeding equipment. Raw coal is screw-fed to the coal mill from a silo (Fig. 5). Hot air dries out the pulverized coal and transports it via a cyclone and a filter into a secondary silo. Through a

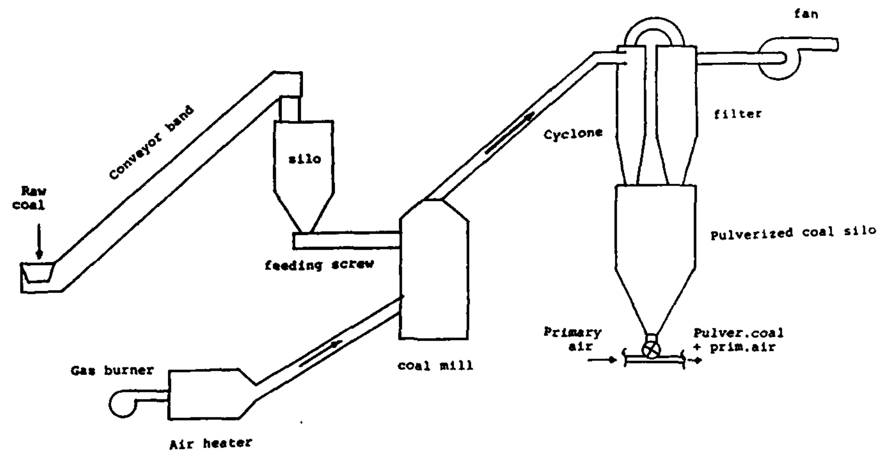


Fig. 5. Coal mill and coal handling system.

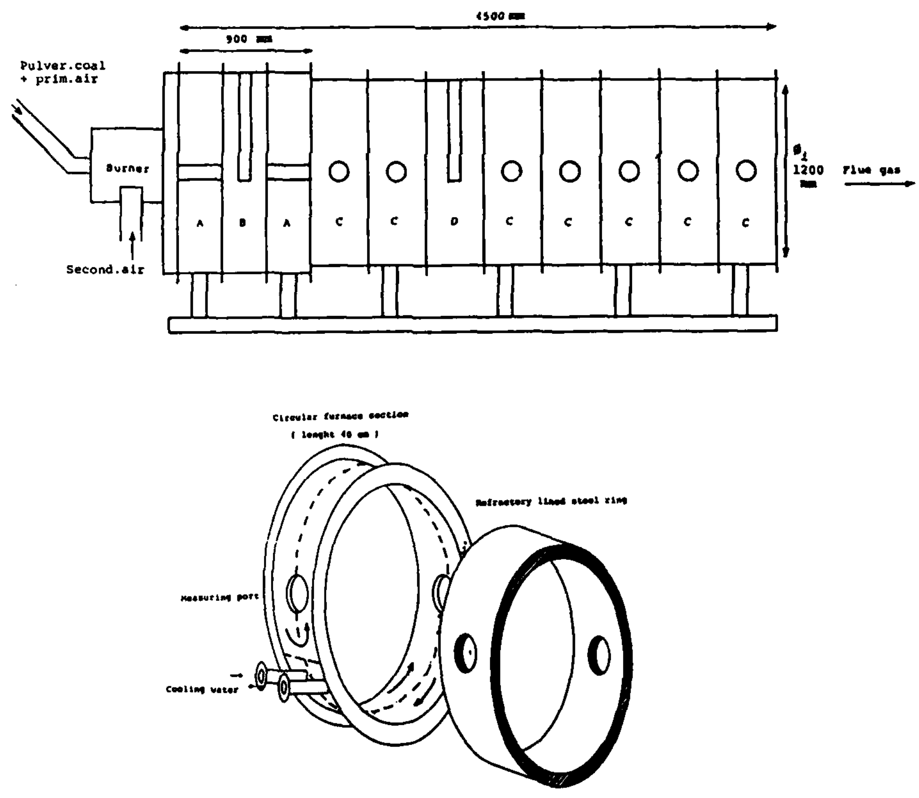


Fig. 6. 2-MW pulverized coal-fired furnace.

rotary cell lock in the bottom of this the pulverized coal can be added to the primary air and be transported to the burner. Secondary air is added in the burner to generate a swirling flame.

The furnace has different port types to allow local measurements: circular, horizontal and 180° vertical-section ports. The experimental furnace has been instrumented to a degree where it is possible to measure all important parameters. A computer samples all data from the experiments. The following parameters is measured:

- Primary air flow
- Secondary air flow
- Power from each furnace section
- Power from flue-gas cooler
- Temperature of gas before and after flue-gas cooler
- Pressure in furnace

Local measurements in the furnace will be made with the following water cooled probes:

- Suction pyrometer
- Gas and solid sampling probe

The flue gas will be analyzed for the content of O_2, CO, CO_2, SOx and NOx.

P. Arendt Jensen

2.8. Studies of Laser Methods

The purpose of the project is to study to which degree of accuracy it is possible to use local laser methods in large combustors. During 1988 local laser measurements of velocity and particle size have been prepared for the 2-MW experimental furnace at RISØ. The work is of a theoretical as well as a practical type. The experimental furnace, 1.2 m in diameter, is in the first test mounted with a 700-kW coal-dust burner (see section 2.7.). Two-dimensional velocity measurements, for cold as well as burning coal particles, will be performed with a Laser Doppler Anemometer (LDA) system in back scatter mode. Later on particle velocity, size and concentration of the coal particles will be measured.

To make the measurements practically possible a specially designed traversing system was designed and built. A clean air supply will keep the environment around the sensitive LDA equipment clean. Measuring ports are specially designed to keep windows clean. The local laser measurements will be difficult because of the extreme conditions, high temperature gradients, dusty environment and the natural variations in particle sizes and concentrations. In order to obtain measurements where gas and particle flows are obtained separately, it is necessary to measure both particle sizes and velocities.

To select the optimum method for particle sizing in the furnace a detailed theoretical work on light scattering has been done. The scattered light from a particle passing through a small volume defined by two crossing laser beams can be collected by a lens and converted to an electrical signal. The signal or the Doppler burst can be analyzed and velocity and size of the particle may be found. Two main parameters are of interest here for particle sizing, the amplitude (pedestal of the burst) and the modulation (visibility of the burst) of the signal. It is known that back scatter measurements are problematic when the particle size and shape are not well defined (i.e. are not mono sized spheres).

The theoretical analysis indicates that back scatter detection gives no information of the particle size (Fig. 7). In forward scatter or near forward scatter it can be shown that the signal amplitude keeps information about the particle size. Furthermore, the visibility curve is well behaved as seen in a typical example in Fig. 8. An example of a polar plot of the light scattering with respect to increasing particle absorption is given in Fig. 9, which shows that the light scattering in back scatter is influenced by the absorption characteristics of the particle material. The studies lead to the conclusion that forward scattering must be used to obtain size information.

The work will be continued with practical flow measurements in the 2-MW furnace.

S. Clausen

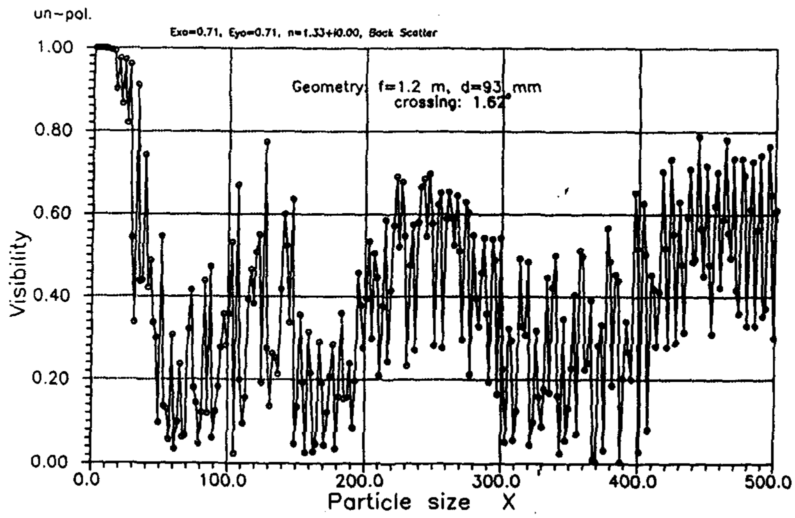


Fig. 7. Result of Mie calculation in back scatter. The shape of the visibility curve and the modulation of the Doppler burst is chaotic with large oscillations. The signal is strongly dependent of the optical properties of the particle material. X is the dimensionless size parameter proportional to particle diameter.

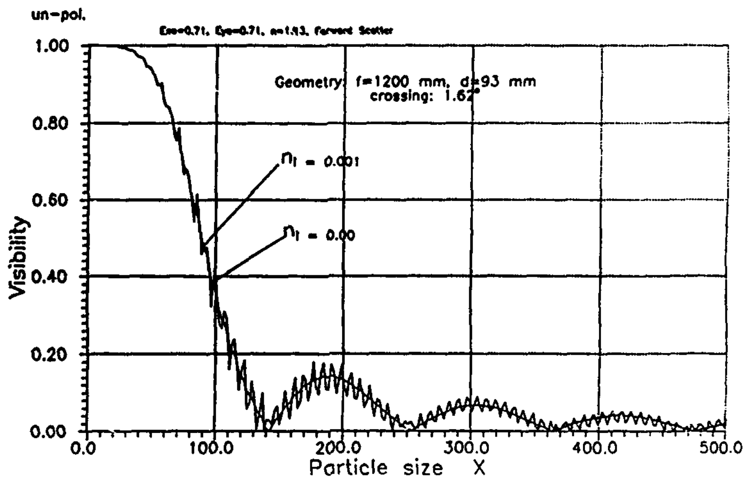


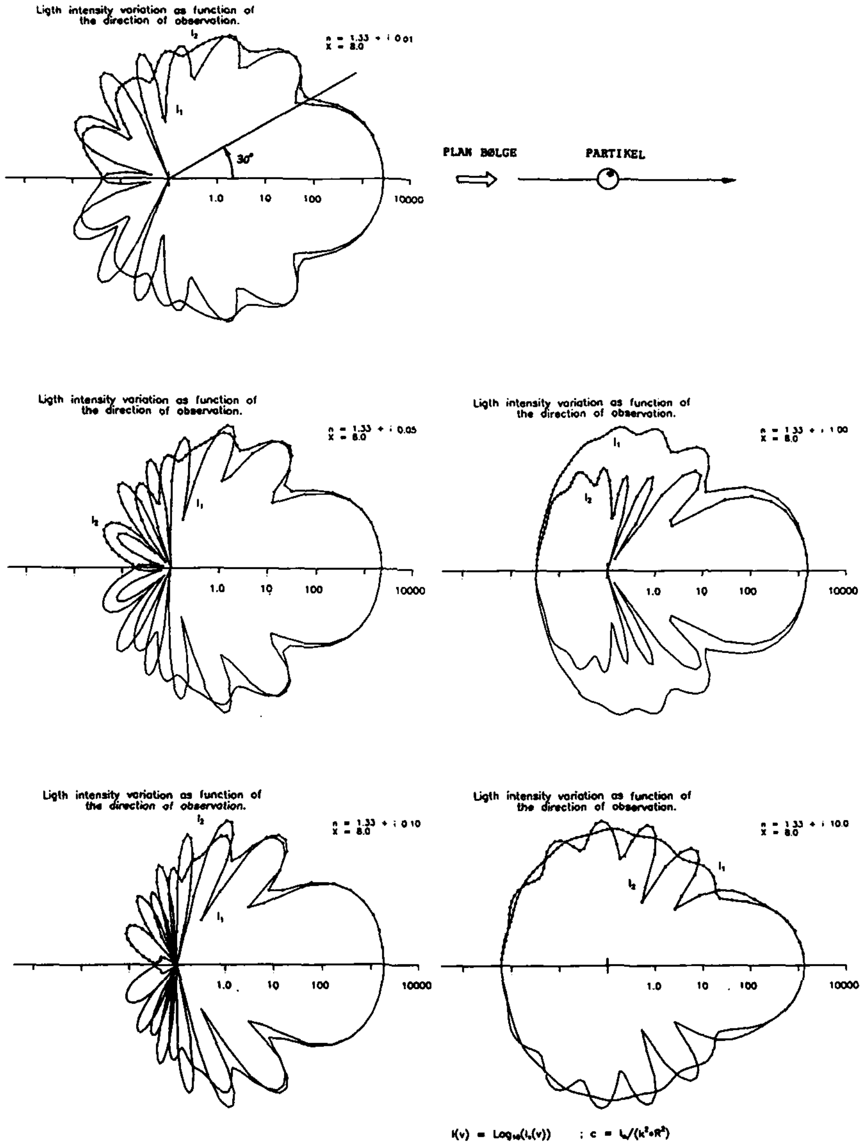
Fig. 8. Result of Mie calculation in forward scatter. The shape of the visibility curve is characteristic. Small oscillations come from inter reflections and are smoothed out by absorption in the particle.

2.9. Large scale Laboratory tests of Two-phase Flow Phenomena

A combined experimental and theoretical study of interface friction in two-phase stratified flow has been carried out as a joint project between Risø National Laboratory, LICconsult Consulting Engineers Ltd. and the Institute of Hydrodynamics and Hydraulic Engineering at the Technical University of Denmark.

The experiments have been made in a test rig located at the Technical University. The rig is about 50 m long including a test section of 36 m with an inner diameter of 90 mm. The test section is partly made of transparent tubes, which makes it possible to determine the flow regime visually.

All experiments have been performed with air/water mixtures at horizontal or near horizontal flow. The inclination of the test



<u>Fig. 9.</u> Polar plot of the scattered light from a particle under variation of the absorption. X = 8 (1.3 micron particle). It's easily seen that the light scattering in back scatter is changed dramatically, but is kept fairly constant in forward scatter, near 0 degree.

section ranging from 0.5^{o} upwards to 1.0^{o} downwards. In total more than 400 combinations of waterflow, airflow and inclination have been investigated.

The equivalent interfacial roughness has been calculated from measurements of liquid and gas velocities, pressure gradient and liquid level in the pipe. The interfacial roughness is ranging from 0 - 90 mm.

This work was carried out in 1987-88 for the Danish Ministry of Energy and has been reported in KAISER and IVERSEN (1988).

In 1988 a new project has been started as a continuation of the above mentioned work. The main purpose of the new programme is to study the transition from stratified two-phase flow to slug flow and to find under which circumstances this transition takes place.

This work is also carried out for the Danish Ministry of Energy.

N.E. Kaiser

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2.10. Computer Modelling of Steady Three-dimensional Turbulent Gas/Particle Flows

Gas/particle flows are found in many industrial applications such as cyclone separators, pneumatic transport of powder and droplet combustion systems. The aim of the present work is to model the flow and combustion of coal particles with special reference to conventional furnaces for pulverized coal combustion.

Three main parts of the model can be identified. First the turbulent flow of the gas and particles has to be determined. The second part models the devolatilization and combustion of volatiles and the combustion of the char residue. Finally, the thermal radiative heat flux between the gas, particles and walls of the furnace has to be modelled.

The work is organized as a joint project with the Laboratory for Heating and Air Conditioning at the Technical University of Denmark.

The project has included development of a computer code that predicts three-dimensional turbulent gas flows by use of k-ε turbulence model and finite element numerical technique. The code also includes gas combustion and radiation. A Lagrangian approach has been used to model the particle motion, and the gas particle momentum interaction is modelled as aerodynamic drag. The gas velocity "seen" by the particle is the mean velocity supported by the gas flow code superimposed a random velocity fluctuation. The computer code to predict particle motion has been described by ASTRUP (1988), while particle behavior in general has been treated by DALL (1988).

E. Gjernes

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2.11. Gasification of Straw, Literature Review

The first part of an EFP-88 project, Combined Fluid Bed Gasification of Straw, has been completed. The EFP project is carried out as a cooperation among Aalborg Boilers A/S, dk-TEKNIK, and the Section of Combustion, Risø. The aim of the work is through a literature study and calculation to establish a technical basis for the development of a straw gasification plant. The first part of the project contains a theoretical and technical study of the conditions which are significant for the choice of reactor type and flue gas cleaning system.

Based upon the literature study the conclusion is that gasification of straw theeoretically should be possible with a satisfying result. The main problem is the risk of slagging and content of tar derivatives in the product gas. It should be possible to minimize the problem of slagging by use of a fluid bed reactor with air as the gasification agent. The content of tar derivatives in the product gas can be kept at an acceptable niveau for an engine or gas turbine by use of catalytic cracking. Calcined dolomite will probably be suitable as a catalyst.

2.12. Oil Recovery from Fractured Reservoirs

For naturally fractured reservoirs it is important to understand the multiphase flow processes involved in the exchange of oil, water, and gas between the fractures and the matrix blocks constituting the porous rock between the fractures.

The dual-porosity, dual-permeability concept is a widely accepted approach to the solution of fractured reservoir problems. In this concept the fracture network and the matrix blocks are treated as two overlapping continua. In full-field simulations, however, computer capacity limitations dictate the application of very coarse calculation grids, each grid block encompassing many fractures and matrix blocks. Hence, the fracture - matrix phase exchange must be described in terms of lumped-parameter models. One such model is implemented in the COSI simulator developed at Risø. However, a variety of phase-exchange models have been suggested in the literature, and further development and investigations of the reliability of such models under various recovery conditions are required.

In the present collaboration project the basic flow phenomena are studied both experimentally and theoretically. Bead-pack experiments in a transparent box with water displacing oil from a matrix block into an adjoining fracture have been conducted at the Laboratory for Energetics at the Technical University of Denmark. Our detailed computer simulations of these experiments gave results in reasonable agreement with the experimental results. Further experiments are in progress at the Geological Survey of Denmark, using artificially fractured chalk cores similar to those from the North Sea oil fields.

In such simple geometries, using a traditional simulator, one can afford a sufficiently fine mesh to approximate the saturation and pressure distributions occurring within the single matrix block to a reasonable degree of accuracy. The idea then is to use the verified fine-grid model for reference calculations when testing various phase-exchange models for the coarse-grid, dual-porosity simulator.

In order to get the necessary insight into the phase exchange process under various conditions, the displacement of oil by water from a matrix block has been investigated parametrically with the flow equations expressed in dimensionless form. The work is presently at the reporting stage. In the example presented below, the results are converted back to dimensional form using typical North Sea reservoir data.

The example illustrates the complex problem of wettability effects on the oil recovery from fractured reservoirs. Wettability is closely related to the contact angle of the oil-water interface against the pore wall. The oil-water pressure difference caused by interfacial tension of the curved interfaces is the capillary pressure, which is a function of the water saturation, i.e. the fraction of pore volume filled with water.

If the rock is preferentially wetted by water, the oil-water capillary pressure P_c is positive up to high water saturations S_w as shown in the inset of Fig. 10. Then an oil-saturated matrix block flooded by water will imbibe the water like a sponge, while the oil is expelled into the fracture system and may be transported to the production wells. The oil recovery versus time is shown in Fig. 10 with solid line for two rather large blocks (2 and 20 m) using normal formation water. Here addition of surfactants to reduce the interfacial tension, and hence the capillary pressure, has an adverse effect on the recovery time as shown by the dashed curves. Furthermore, the risk of changing the wettability by the surfactants should be considered.

If the rock is preferentially wetted by oil, the capillary pressure becomes negative for practically all saturations and hence opposes the oil extraction. For intermediately wet rock, having no strong wettability preference, the capillary pressure changes from positive to negative values somewhere between the endpoint saturations. In the case with intermediate wettability shown in Fig. 11, where the capillary pressures are relatively weak and negative over almost the whole saturation range, some oil can be recovered due to buoyancy effects, but the process is slow and the ultimate recovery is poor, especially for small blocks. In this case surfactants improve the recovery (dashed curves).

Thus, while the surfactant method may be attractive for homogeneous reservoirs, great caution is warranted for fractured reservoirs. For non-fractured reservoirs the capillary pressures are inferior to the flow pressure drops towards the wells and hence the wettability becomes less important. Here the main advantage is that the surfactants reduce the residual oil saturation, thus increasing the amount of mobile oil. For fractured reservoirs this effect may be overshadowed by the other effects discussed above.

The Danish North Sea reservoirs are usualy assumed to be water wet, and it is customary (as in Fig. 10) to use capillary pressures obtained by mercury injection and scaled with the inter-

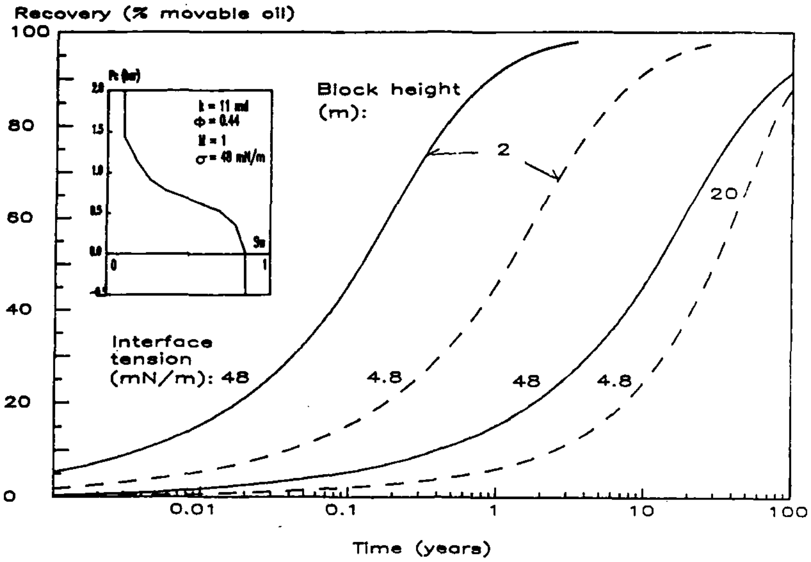

Fig. 10. Imbibition and gravity displacement of oil by water from fully submerged, strongly water wet matrix blocks (1-D).

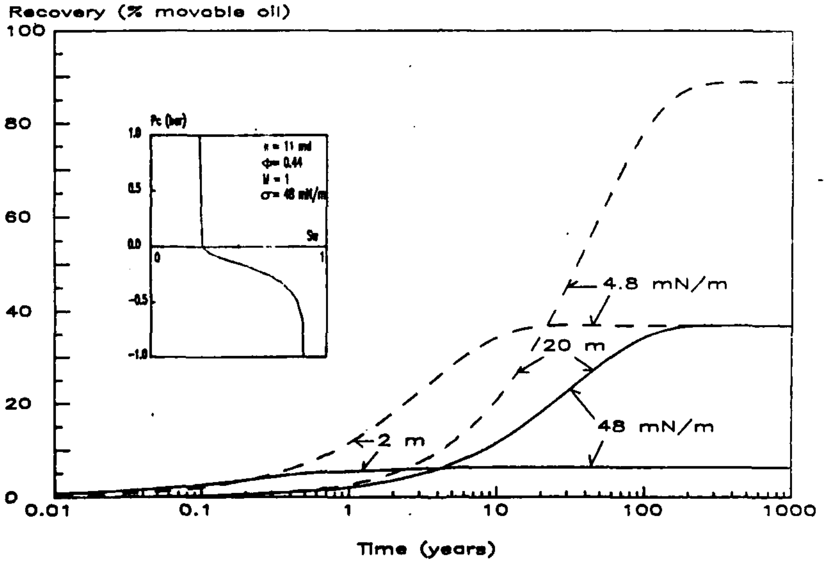

Fig. 11. Gravity displacement of oil by water from intermediately wet matrix blocks, fully submerged (1-D).

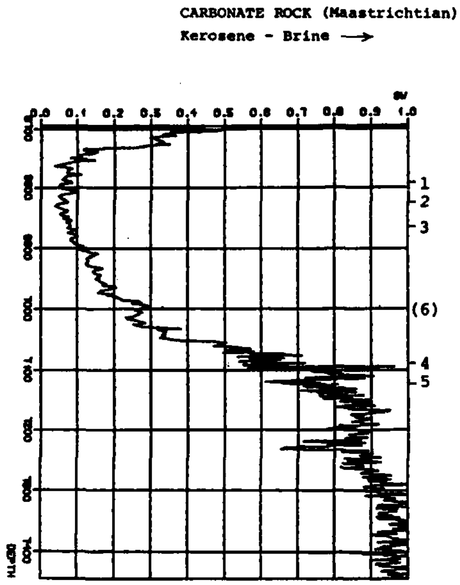

Fig. 12. Water saturation log (well N-3). Core reference numbers for Fig. 13 are indicated at the right.

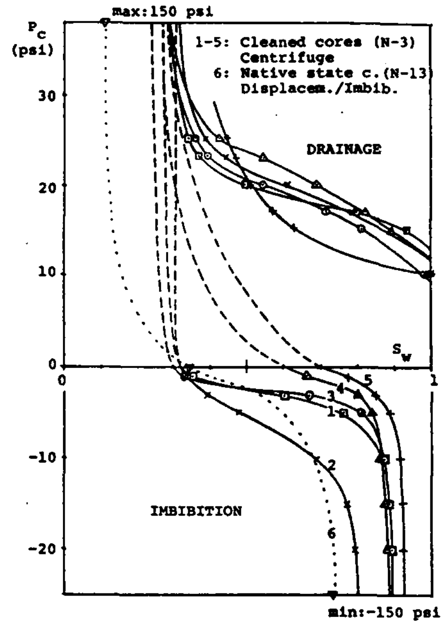

Fig. 13. Capillary pressure P_c versus water saturation S_w for Gorm field cores, showing wettability variation.

face tension ratio. However, such data seem to be in contradiction with the few available measurements made with an oil-water system (see Fig. 13). Noting that the capillary pressure exhibits hysteresis, the relevant part of the hysteresis loop is the imbibition branch (the lower curves with increasing S_w). Although most of the cores are cleaned, they are intermediately wet with a striking correlation between the wettability preference and the original saturation environment of the cores (cf. Fig. 12). Unfortunately, imbibition data are lacking in the positive-P_c range due to incomplete measurement techniques, and the data may be unreliable due to the core handling techniques. With Fig. 11 in mind (using the curve for core 1), however, there should be a great incentive for further investigations.

K. Ladekarl Thomsen

2.13. The Temperature Field around a Hot Magma Sheet

Hot magma bodies with temperatures up to 1200°C are now and then injected into the upper crust of the Earth. The country rocks close to the intrusions are drastically altered due to the heat. Thus, f.ex. potential hydrocarbon source rocks begin to generate hydrocarbons by degradation of its content of organic matter. The heat will also initiate diagenetic processes in the mineral matrix. Another effect is annealing of fission tracks in the minerals. Fission track measurements are used for datings and for determination of thermal history. Fission tracks are tracks of crystal dislocations in the minerals due to spontaneous fission of U-238. The dislocations are annealed at elevated temperatures as a function of time. The present study was initiated to investigate the effect of an intrusive horizontal magma sheet in Sweden, on fission tracks measured 160 m below the intrusion (ZECK et al., 1988).

The liquid magma is assumed to be momentaneously injected into the sedimentary layers. It is assumed that the magma body gives up its heat to the country rocks by conduction. Heat transportation by convection of pore water fluids is neglected. If convection occurs, the cooling rate of the magma body would be somewhat higher than predicted by pure conduction. Latent heat of the minerals is included in the calculations. Both an analytical and a numerical solution approach was used to determine the temperature history. The analytical approach was mainly applied to check that the accuracy of the numerical method was good enough.

An example of calculation of the temperature field around an intrusive sheet is shown in Fig. 14. It is seen that the temperature field is asymmetric around the sheet due to the presence of the earth surface and the natural geothermal gradient. A 100 m thick intrusion is totally cooled in about 10,000 years.

Based upon a number of calculation examples, as the one discussed above (JENSEN, 1989), it could be concluded (ZECK et al.,

1988) that the fission tracks in apatite are totally annealed. In contrast tracks in sphene are hardly affected.

P. Klint Jensen

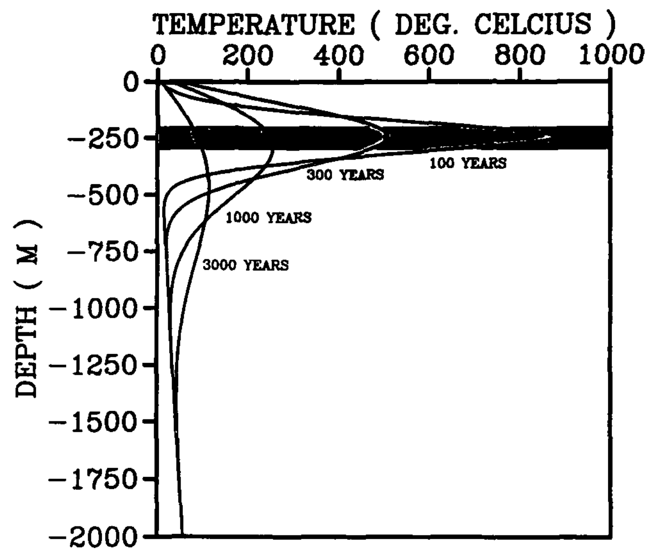

Fig. 14. The temperature field around a hot magma sheet.

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Abstract (Max. 2000 char.)

The general development of the Department of Energy Technology at Risø during 1988 is presented, and the activities within the major subject fields are described in some detail. Lists of staff and publications are included.

Descriptors - INIS

COMBUSTION; HEAT TRANSFER; MATHEMATICAL MODELS; MULTIPHASE FLOW; PETROLEUM; PROGRESS REPORT; REACTOR PHYSICS; RESEARCH PROGRAMS; RESERVES; RISOE NATIONAL LABORATORY.

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